Some recent approaches in

Fast Charge Sensing

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Kai Schwarzwälder
Universität Basel
Outline

- **Introduction**
- **Cryogenic Amplification**
- **rf-QPC**
- **Superconducting rf-SET**
- **Summary**
Introduction: Applications

- charge dynamics in dots
- single-shot read-out
- observe coherent spin dynamics
- single e tunneling in SWCNT [PRB 73, 201402(R) (2006)]
- moving particles in microfluidic channels [APL 87, 184105(2005)]
- metrology [Nature(London)434,361(2005); Science 312,1634(2006)]
- shot noise studies (5)
Introduction: Q factor

\[ Q = \omega \frac{E_{\text{stored}}}{P_{\text{lost}}} = \ldots = \frac{f_0}{\Delta f} \]

- "2\pi * \text{energie ratio lost in one period}"
- \( Q < \frac{1}{2} \) overdamped
- \( Q = \frac{1}{2} \) critically damped
- \( Q > \frac{1}{2} \) underdamped
- radio receiver
  - small Q ⇒ easy to tune but noisy, disturbed by neighboring radio stations
  - large Q ⇒ difficult to tune but clear signal

Damped spring:

\[ Q = \sqrt{\frac{mk}{R}} \quad \omega = \sqrt{\frac{k}{m}} \quad F = -Rv \]

RLC series:

\[ Q = \frac{1}{R} \sqrt{\frac{L}{C}} \quad \omega = \sqrt{\frac{1}{LC}} \]
Introduction: Signal loss

- parasitic capacitances
- RT noise
- MNK-I:

\[ C_P \approx 1 \text{nF} \]
\[ R_W \approx 600\Omega \quad \Rightarrow f_c \approx 265\text{kHz} \]
Introduction: Signal transmission

- coaxial lines:
  „lumped“ circuit

Two ways out:
1. cryogenic amplification
2. impedance matching
   i. rf-QPC
   ii. rf-(S)SET

\[
Z = \sqrt{\frac{R+i\omega L}{G+i\omega C}}
\]
Cryogenic Amplification: Basics

- Idea:
  - Lower $C_P \rightarrow$ higher BW
  - Lower (RT) noise effects

- Tradeoff: $R_C$, $C_W$

- HEMT:
  - Agilent ATF 35143
  - $g_m = 10 \text{mA/V}$
  - Gate: $400 \mu\text{m}$
  - $P_{\text{diss}}: 30 \mu\text{W}$

- Bandwidth:
  \[ BW = \frac{1}{2\pi R_C C_W} = 1\text{MHz} \]
Cryogenic Amplification: Noise

\[ S_I = \frac{2e^2}{h} \sum_i N_i \left[ eV_{\text{QPC}} \coth \left( \frac{eV_{\text{QPC}}}{2k_B T_e} \right) - 2k_B T_e \right] \]

- \( T_e = 255 \text{mK} \) (fit)
- \( T_e = 267 \text{mK} \) (Coulomb peaks)
Cryogenic Amplification: Dot Population

\[ \Gamma f(\mu) \left( 1 - f(\mu) \right) \]

\[ T_e = 255 \text{mK} \quad \Gamma = 26.1 \text{kHz} \]
Principles of rf-QPCs

- **AlGaAs/GaAs**
  \[ \rho = 1.7 \cdot 10^{15} \frac{e}{m^2} \]
  \[ \mu = 80 \frac{m^2}{Vs} (4.2K) \]
  \[ d = 90 \text{nm} \]
Characterising rf-QPCs

\[ V_{\text{gate}} = V_G^0 + V_{ac} \sin \omega_s t \]

ac-signal induces charge fluctuations \( \Delta q \)

\[ \delta q = \frac{\Delta q}{\sqrt{BW} 10^{\frac{SNR}{20}}} \approx 2 \cdot 10^{-1} \frac{e}{\sqrt{\text{Hz}}} \]
rf-QPC for charge sensing: set-up

- AlGaAs/GaAs
  \[ \rho = 2 \cdot 10^{15} \frac{e}{m^2} \]
  \[ \mu = 20 \frac{m^2}{Vs} \]
  \[ d = 100 \text{nm} \]
  \[ T_e = 120 \text{mK} \]
rf-QPC for charge sensing: Properties

- Charge sensitivity
  \[ \delta q \approx 10^{-3} \frac{e}{\sqrt{\text{Hz}}} \]
- Q-factor limits SNR

(2)
rf-QPC for charge sensing: e-hopping

- distortion due to heating and capacitive coupling
  → blanking scheme
rf-QPC at shot noise limit: SAW

- rf drives SAWs
- coupling between shot noise and mechanical degree of freedom
rf-QPC at shot noise limit: Kondo

- zero-bias anomaly similar $P_{in}$ and T dependence as noise power
  \[ \rightarrow 0.7\text{-structure} \rightarrow \text{Kondo} \]
Superconducting rf-SET

- Why superconducting?
  - $C_p$ smaller $\rightarrow$ BW higher
  - extendable
  - negligible loss $\rightarrow$ more sensitive to $R_q$
- $^3$He-Fridge, 290mK
- HEMT, 2.8K
Superconducting rf-SET

- IV-curve for various $V_g$
- Properties for sample A/B:
  
  $E_C = \frac{e^2}{2\Sigma} = 205\,\mu\text{eV}/220\,\mu\text{eV}$
  
  $R_n = 25\,\text{k}\Omega/26\,\text{k}\Omega$

- optimal sensitivity ≠ optimal impedance match
Superconducting rf-SET

- comparison with commercial inductor

- HEMT noise:
  - $P_{\text{HEMT}} = 210\text{aW}$

- Charge sensitivity

\[ \delta q = \frac{q_0}{\sqrt{2BW10^{SNR/20}}} \approx 2.4 \cdot 10^{-6} \frac{\text{e}}{\sqrt{\text{Hz}}} \]
## Summary

<table>
<thead>
<tr>
<th></th>
<th>(4)</th>
<th>(1)</th>
<th>(2)</th>
<th>(3)</th>
<th>(5)</th>
</tr>
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<tbody>
<tr>
<td><strong>Q</strong></td>
<td>NA</td>
<td>10</td>
<td>15</td>
<td>15</td>
<td>20</td>
</tr>
<tr>
<td><strong>BW</strong></td>
<td>1MHz</td>
<td>80MHz</td>
<td>100MHz</td>
<td>60MHz</td>
<td>50MHz</td>
</tr>
<tr>
<td><strong>Charge sensitivity</strong> $\delta q/\sqrt{e/Hz}$</td>
<td>$4.4\cdot10^{-4}$</td>
<td>$2\cdot10^{-1}$</td>
<td>$\sim10^{-3}$</td>
<td>$5\cdot10^{-4}$</td>
<td>$2.4\cdot10^{-6}$</td>
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Conclusions and Outlook

- close to shot noise limit
- charge dynamic events several 100ns
- charge sensitivity limited by .7-structure and mechanical degrees of freedom
- combine techniques
- integrating further devices: MOSFET, Zener diodes, …
Thank you for your attention!!